Role of MHD Dynamo in the Formation of 3D Equilibria in Fusion Plasmas

by

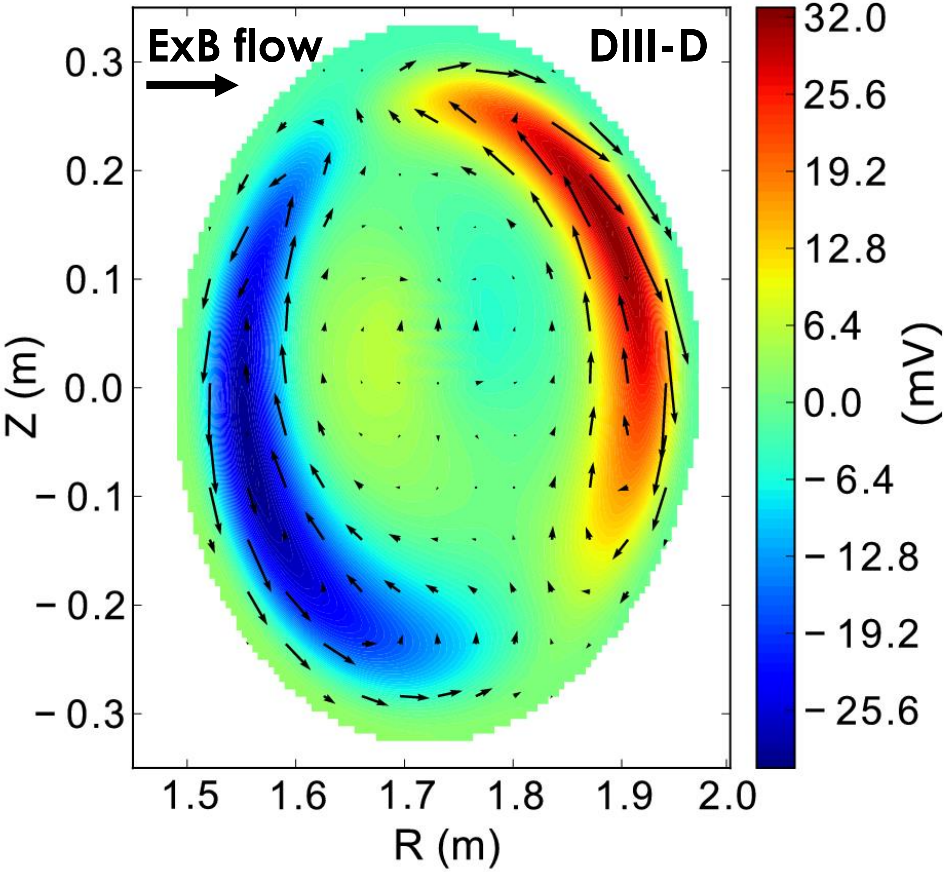
P. Piovesan

Presented at the

26th IAEA Fusion Energy Conference, Kyoto, Japan

October 17-22, 2016

MHD dynamo EMF of helical core



Work supported in part by the US DOE under DE-FC02-04ER54698.

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Authors

P Piovesan, D Bonfiglio, S Cappello, L Chacón, C Chrystal,
DF Escande, P Franz, CT Holcomb, V Igochine, TC Luce,
L Marrelli, MD Nornberg, C Paz-Soldan, L Piron, I Predebon,
JS Sarff, NZ Taylor, D Terranova, F Turco, RS Wilcox,
A Wingen, P Zanca, B Zaniol, the RFX-mod Team,
the MST Team, the DIII-D Team, the ASDEX Upgrade Team,
the EUROfusion MST1 Team

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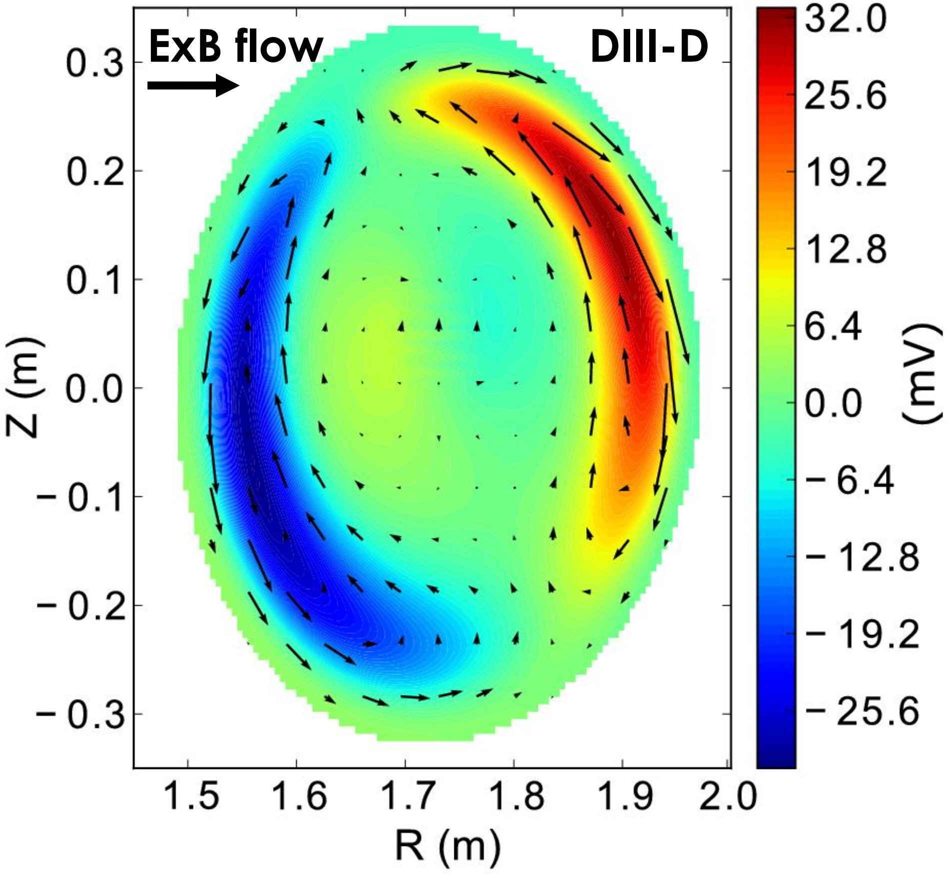
MHD Modes Can Broaden the Current Profile Through a Continuous MHD Dynamo

- **MHD modes often saturate into stationary 3D equilibria**
  - affecting current profile, stability, transport, …

MHD dynamo EMF of helical core



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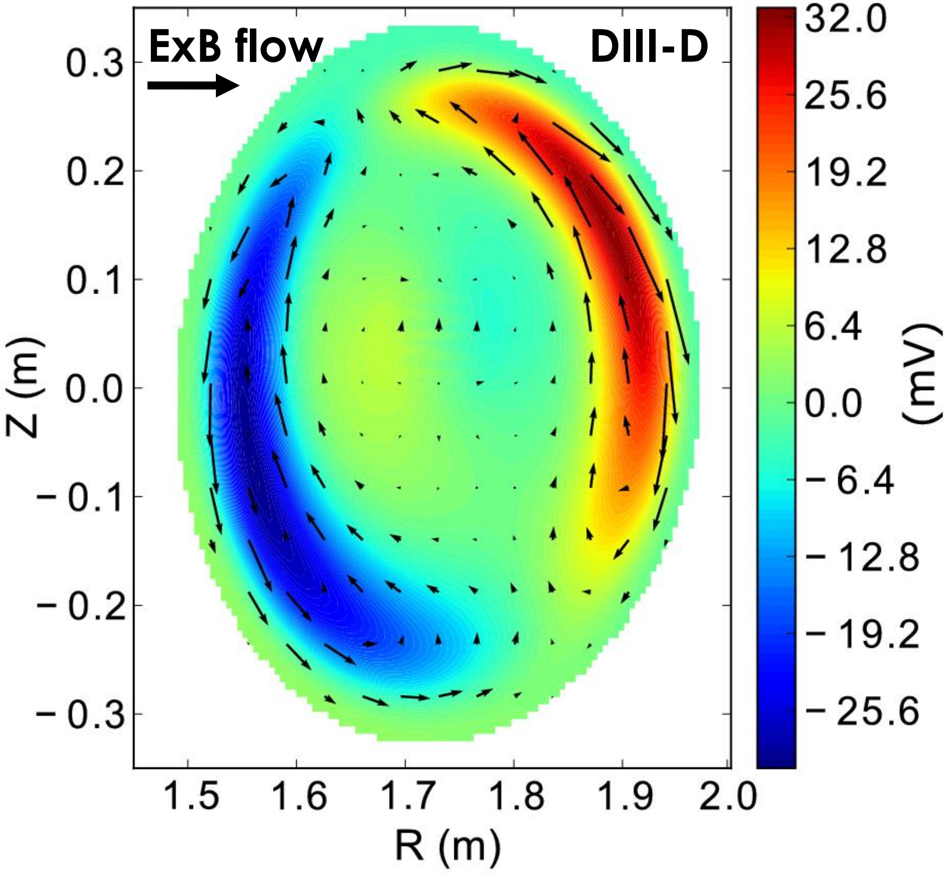
$$\boldsymbol{E}_{loop} + \tilde{\boldsymbol{v}} \times \tilde{\boldsymbol{b}} = \eta \boldsymbol{j}$$

MHD dynamo EMF of helical core



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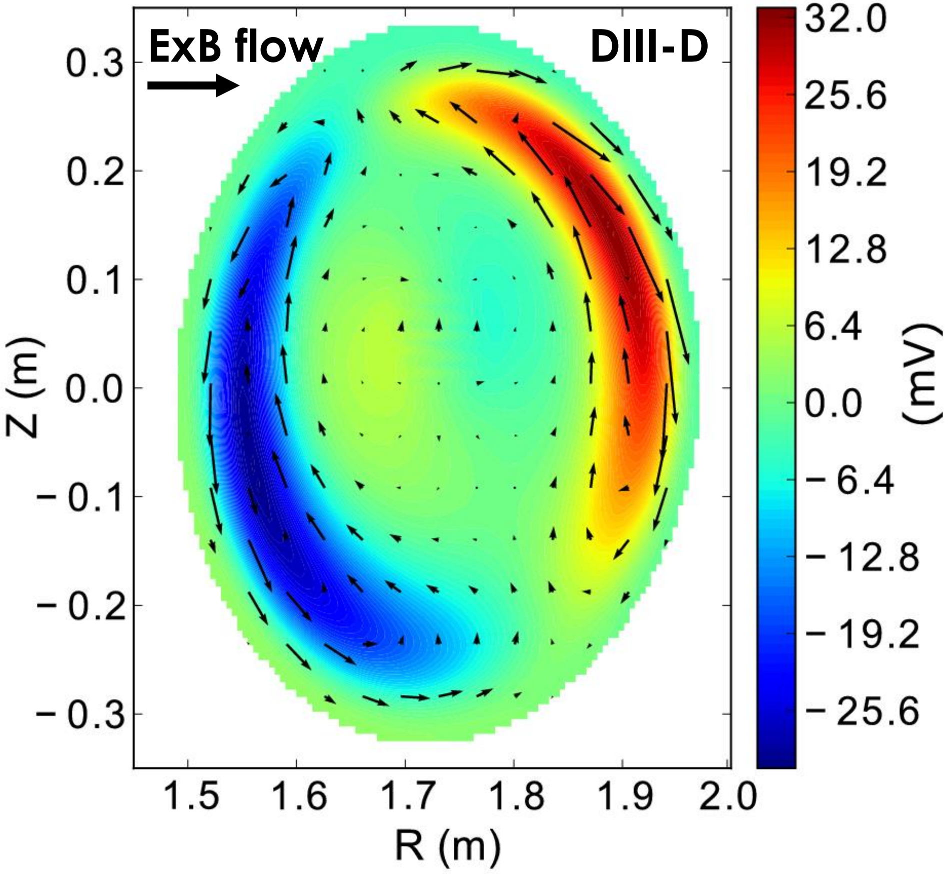
- **Resistive MHD predicts that helical states induce a continuous dynamo EMF:**

$$\boldsymbol{E}_{loop} + \tilde{\boldsymbol{v}} \times \tilde{\boldsymbol{b}} = \eta \boldsymbol{j}$$

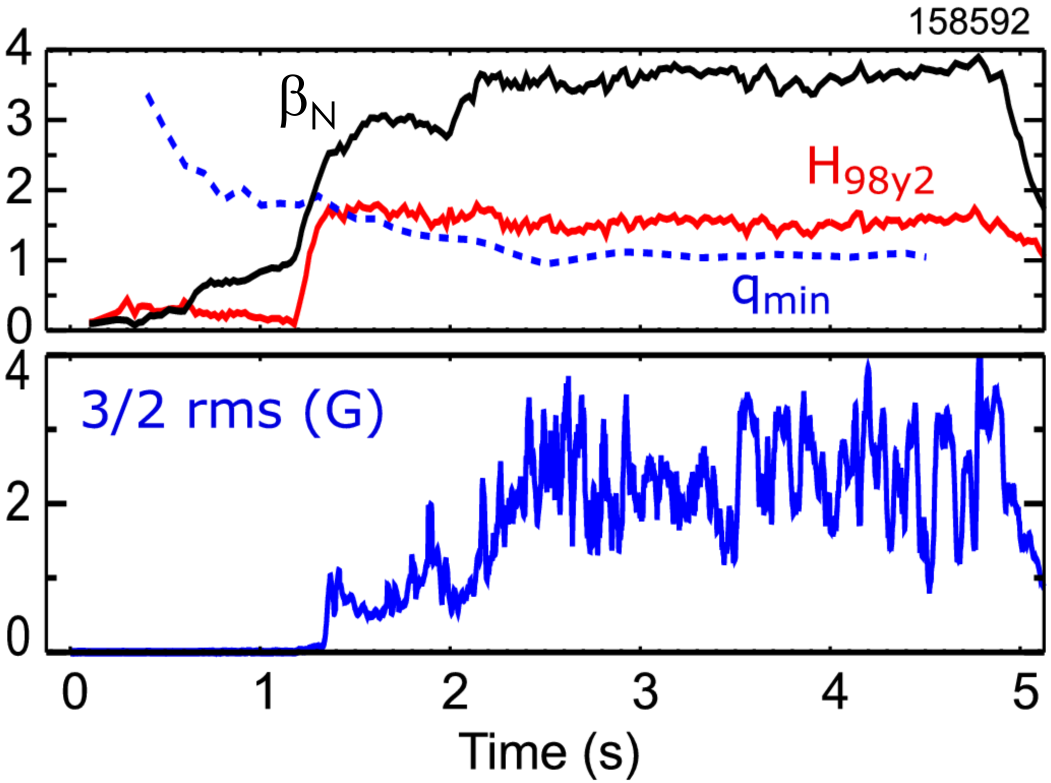
- **Can explain anomalous current broadening in:**
  - high-β hybrid tokamak
  - reversed-field pinch

MHD dynamo EMF of helical core



The Current Profile of Hybrid Tokamak Plasmas is Broadened by Benign MHD

- **Hybrid tokamak: H-mode with improved confinement & high-β**
- **Benign MHD broadens the current profile and keeps q_{min}>1**
- **As a result, no sawteeth, deleterious 2/1 mode more stable**

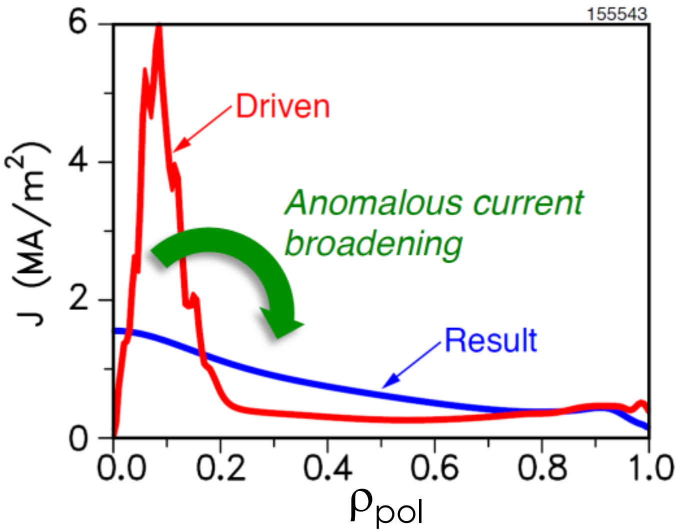


From CC Petty EPS 2015

Anomalous Current Broadening Enables Steady State Hybrid Operation

- **The hybrid scenario has moderate bootstrap current fraction, f_{BS}≈0.5**
- **Can be compensated by efficient EC current driven near the center and redistributed by MHD**

F Turco PoP 2015, CC Petty NF 2016
CC Petty EX/4-1, this conference



Anomalous Current Broadening Enables Steady State Hybrid Operation

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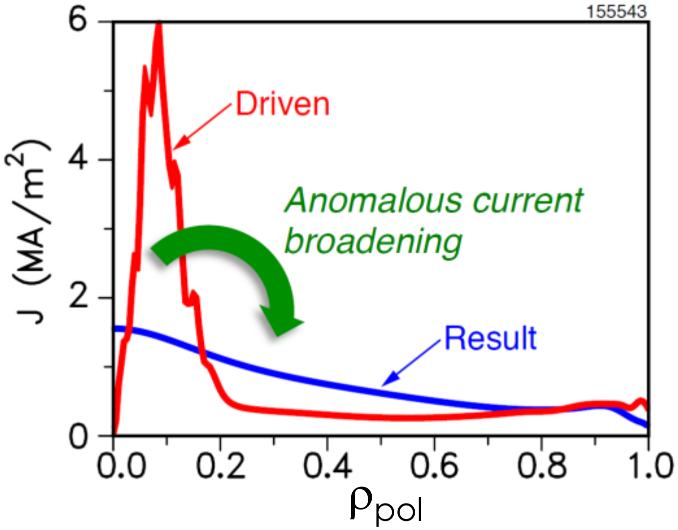

A validated model of current redistribution is needed for extrapolations to future machines

- For example, current redistribution in DIII-D mainly occurs during transient NTM-ELM coupling events [CC Petty PRL 09]
- Will it work in a continuous way in ELM-suppressed plasmas?

Outline

GOAL: Test the MHD dynamo model of current redistribution in fusion plasmas

- A helical core equilibrium forms in hybrid tokamak plasmas perturbed by external n=1 fields
- Helical core used to probe current broadening
- Effect consistent with the MHD dynamo model
- Strong similarity with helical RFP dynamo
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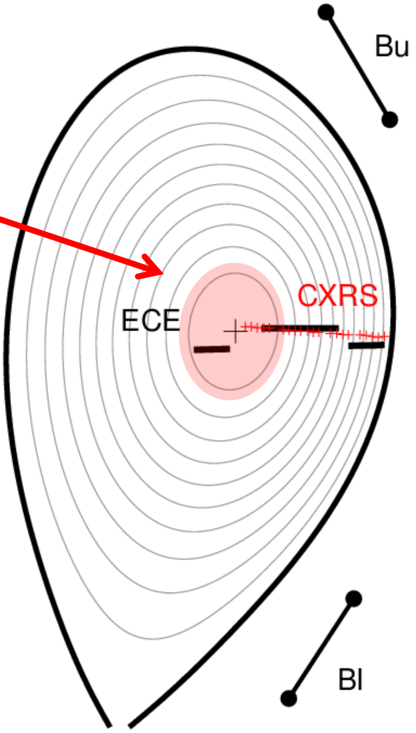
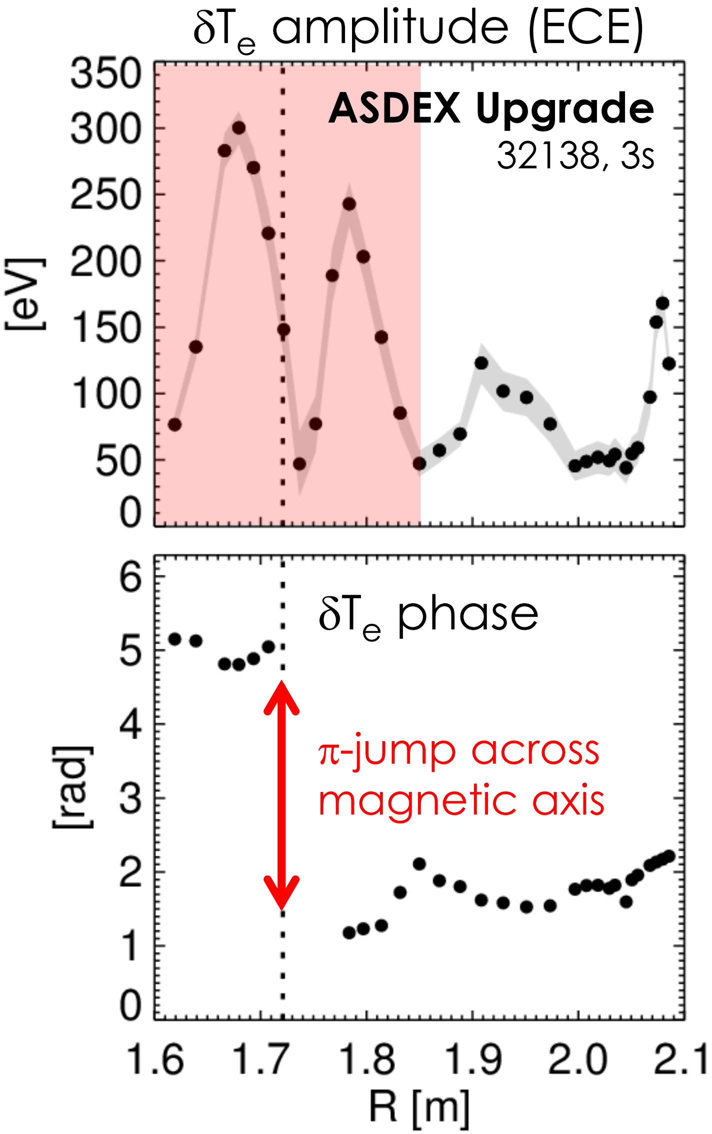
A Helical Core Forms in Hybrid Plasmas Perturbed by External n=1 Fields

- **Helical core due to the response of a marginally-stable kink to the externally applied n=1 field**
- **1/1 harmonic large due to $q_{min} \geq 1$**

P Piovesan EPS 2016
V Igochine EX/P6-24

Helical core
detected by ECE and CXRS as n=1 field rotates at 5Hz

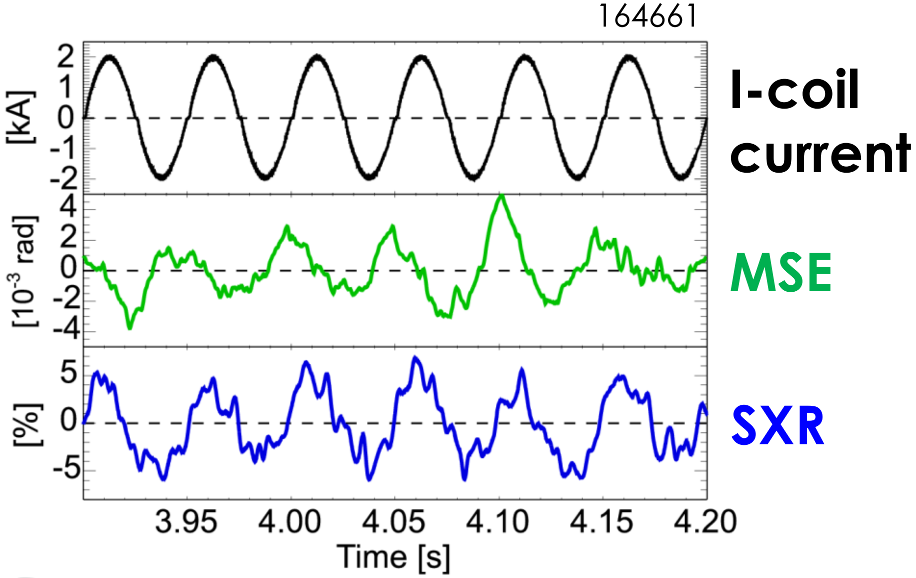




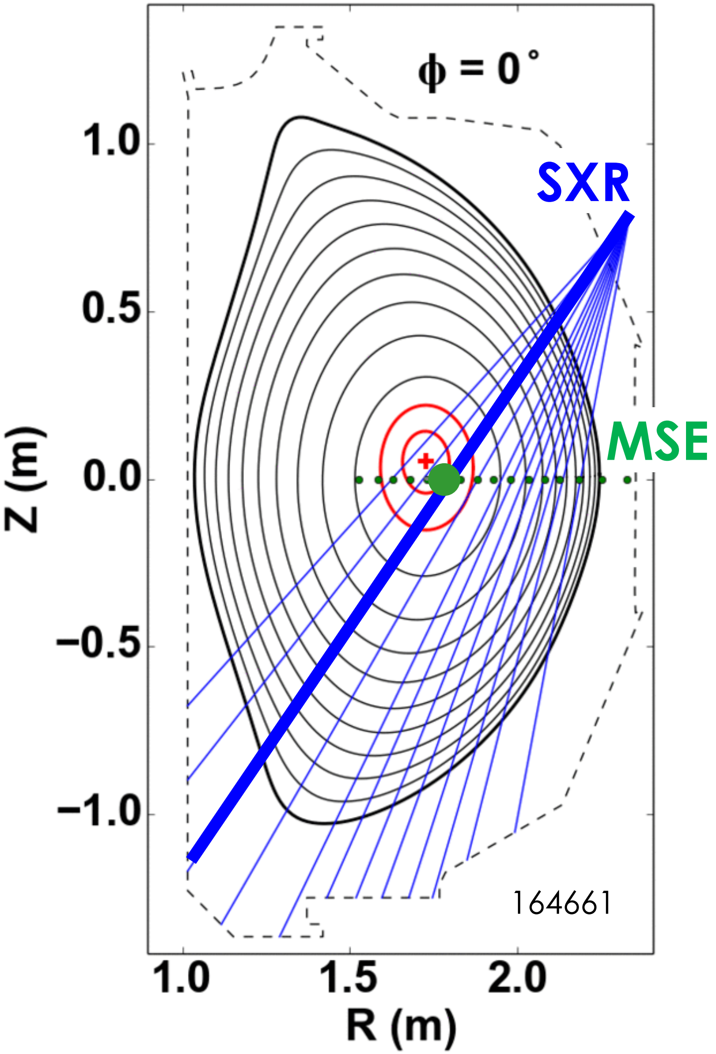
Helical Core Reconstructed by the VMEC/V3FIT 3D Equilibrium Code in DIII-D

- **Helical core reproduced in DIII-D**
- **Reconstructed by VMEC/V3FIT, constrained by SXR and MSE measurements of the internal helical distortion**

A Wingen EPS 2016



Applied n=1 field rotates at 20Hz



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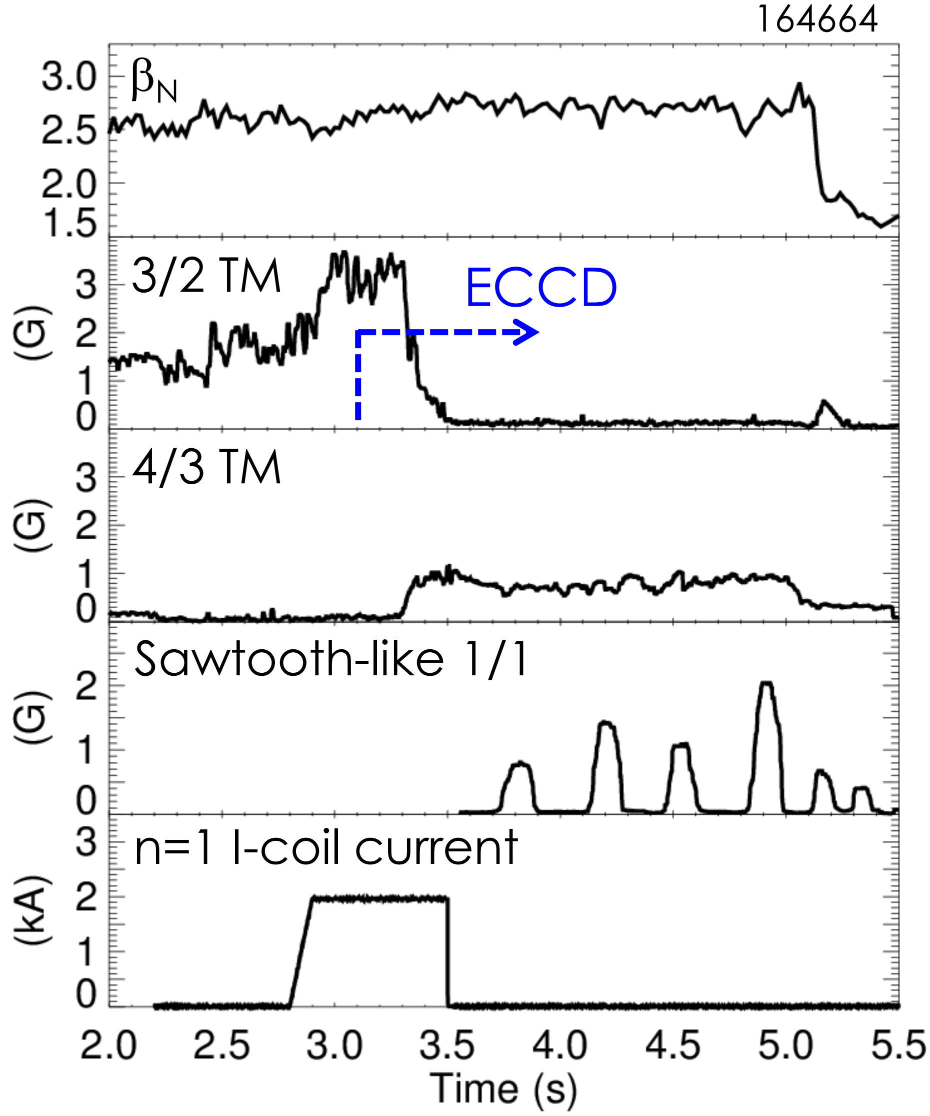
The Helical Core Sustains Hybrid Conditions

- **3/2 tearing mode suppressed by ECCD**

- **Sawteeth come back**
  - Hybrid conditions are lost due to absence of current broadening by the 3/2 TM [MR Wade NF 2005]



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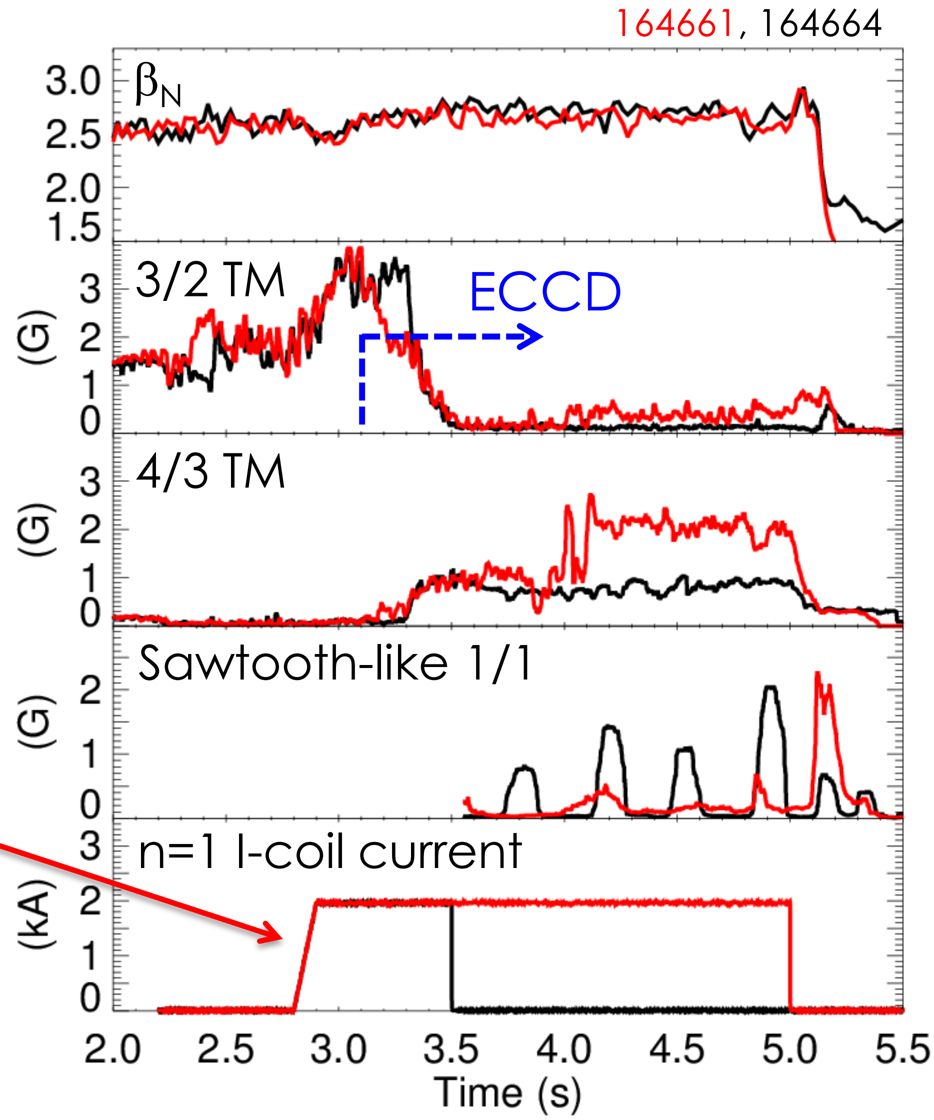
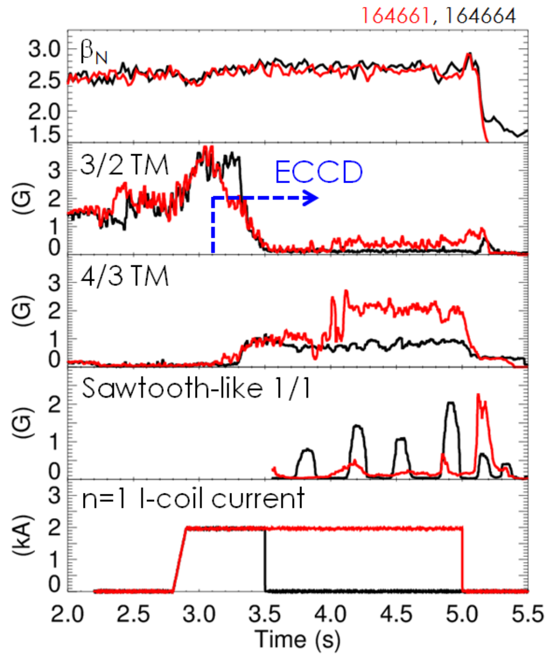
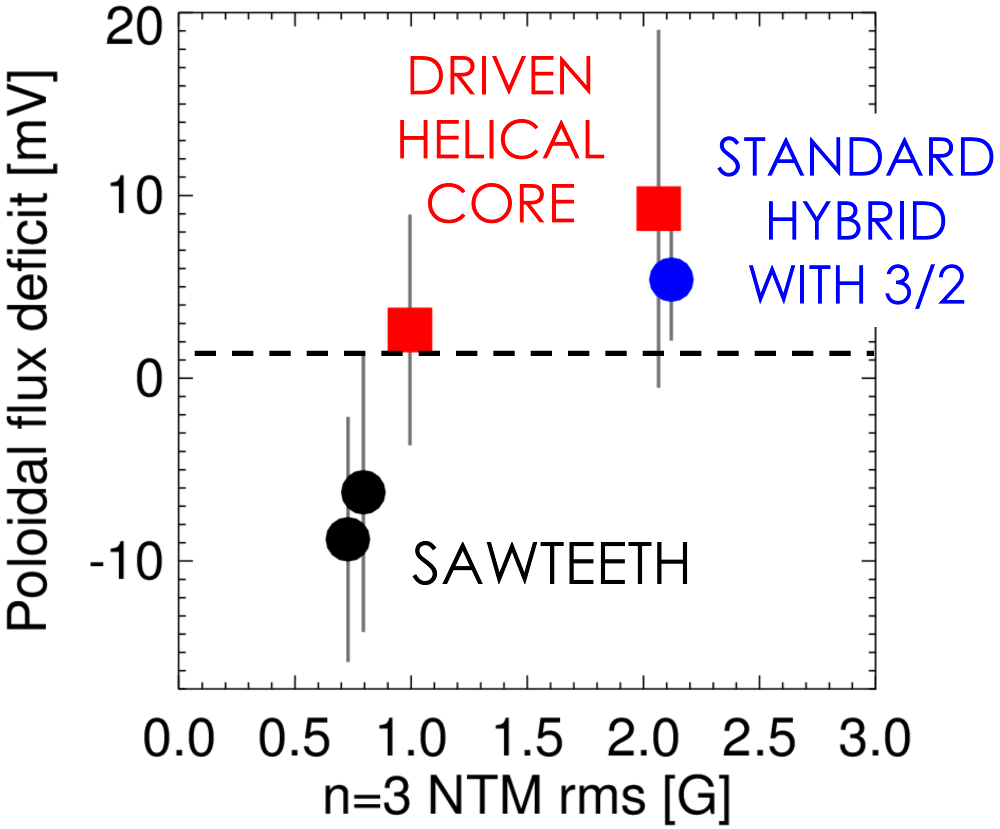
- **No sawteeth when the helical core is induced by an external n=1 field**



The Helical Core Causes a Measurable Level of Central Current Broadening

- **Poloidal flux dissipated at a faster rate than it is supplied by coils**
  - The **poloidal flux deficit** is estimated from the time evolution of the reconstructed equilibrium [TC Luce NF 2014] and is proportional to the amount of current broadening in hybrid plasmas [NZ Taylor APS 2016]





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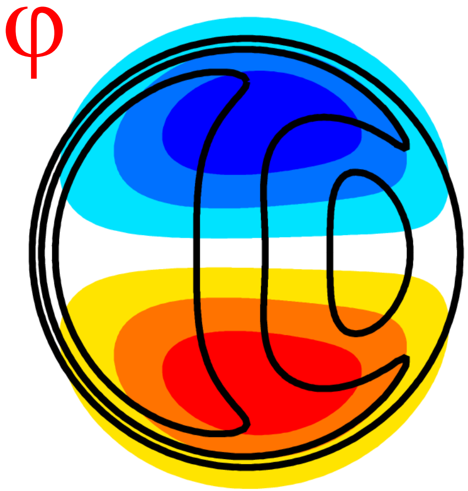
Nonlinear MHD Simulations Predict that a Saturated 1/1 Kink Produces a Continuous Dynamo EMF

- An electrostatic EMF forms in any helical equilibrium to balance the helical modulation of parallel current, $j_{\|}$



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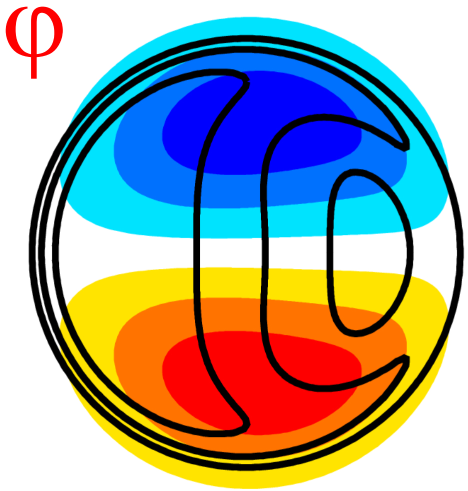
- An **electrostatic EMF** forms in any helical equilibrium to balance the helical modulation of parallel current, $j_{\parallel}$

←

General result that holds both for ***kink*** *and* ***tearing*** *modes.*

Discovered for ***helical RFP*** *by D Bonfiglio PRL 2005 (SpeCyl).*

Recently developed for ***hybrid tokamak*** *plasmas by S Jardin PRL 2015 (M3D-C^1).*



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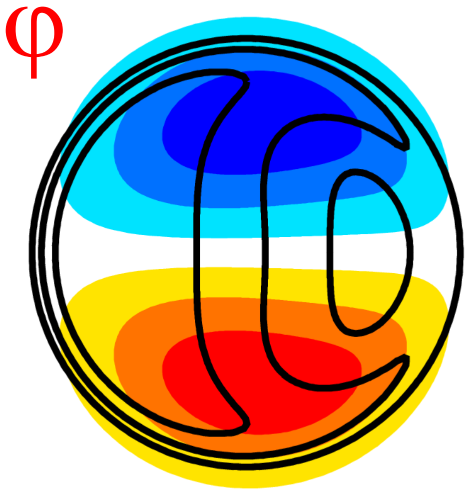

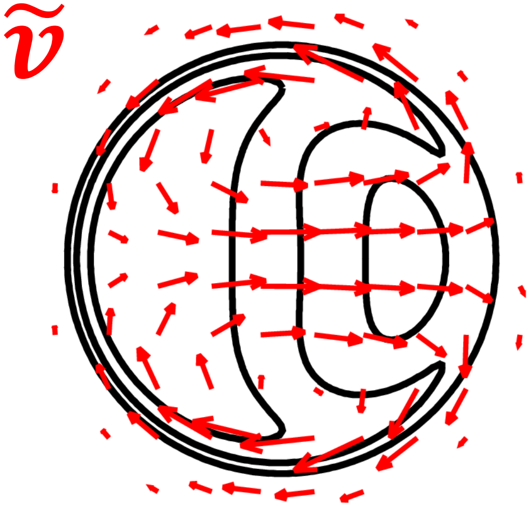

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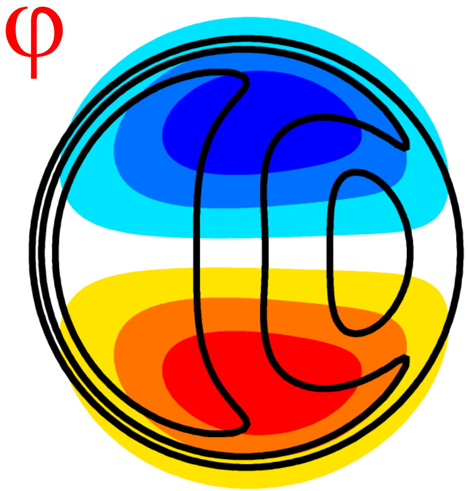
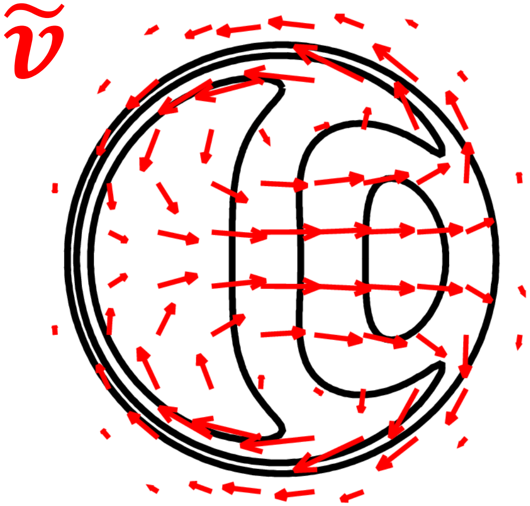
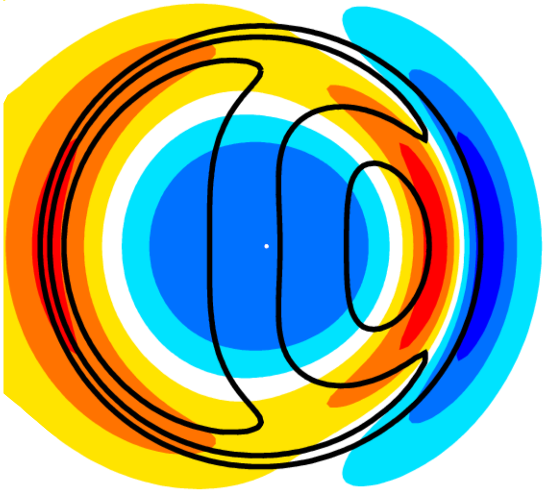
- and produces an electric field in parallel Ohm's law, <u>negative in the core</u>

$$E_{loop\parallel} + \tilde{v} \times \tilde{b}_{\parallel} = \eta j_{\parallel}$$

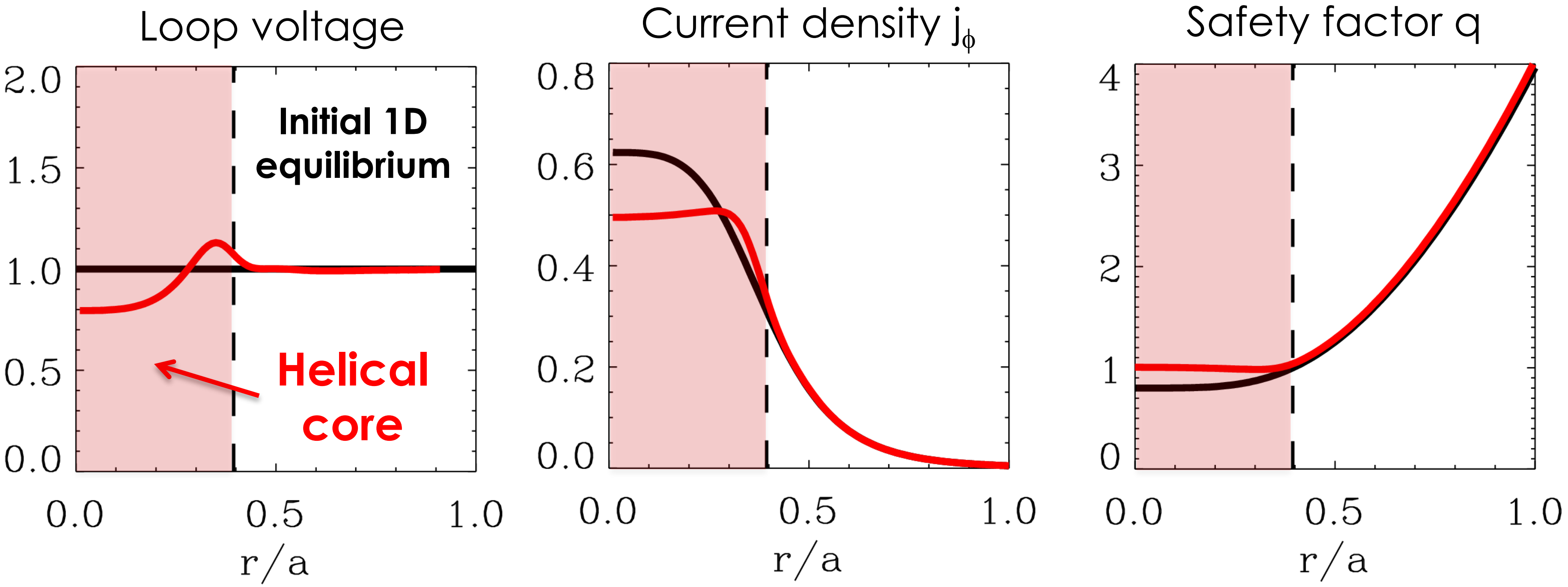






The Dynamo EMF Due to the 1/1 Kink Redistributes Central Current and Keeps $q_{min}\geq 1$

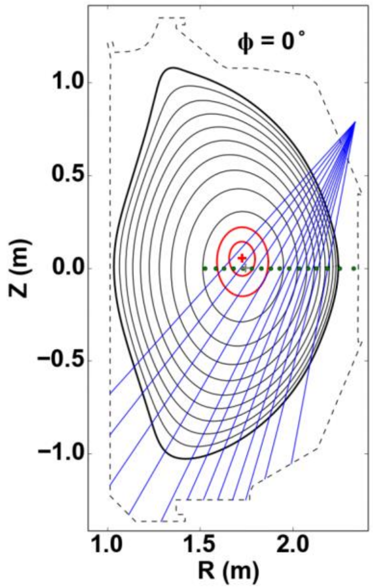
- **The mean-field MHD dynamo EMF opposes the applied loop voltage in the core and redistributes central current**
- **q_{min} raises near/above 1 as the 1/1 kink nonlinearly saturates in the simulation**



More in D Bonfiglio TH/P3-35, this conference

The MHD Dynamo EMF Predicted for the Helical Core is Consistent with the Measured Poloidal Flux Deficit

- **The MHD dynamo EMF can be calculated for the experimental 3D equilibrium, by balancing Ohm's law over 3D flux surfaces:**



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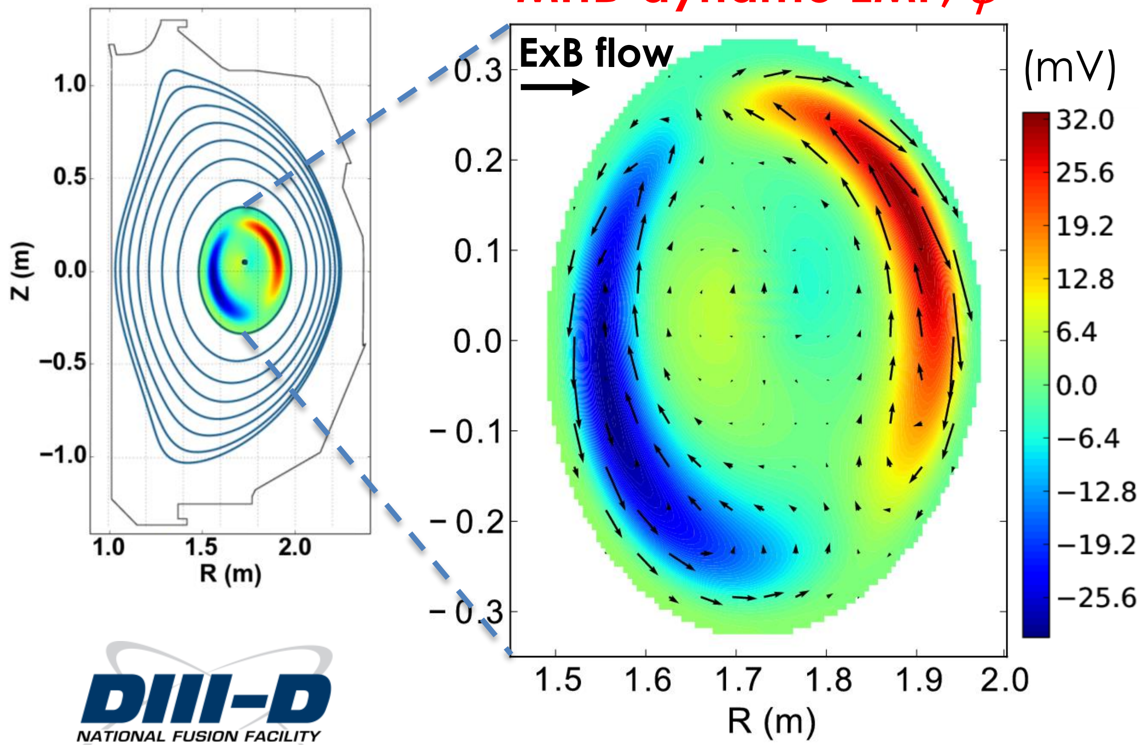
$$\boldsymbol{j}_{Ohm}=\boldsymbol{j}_{VMEC}-\boldsymbol{j}_{CD}-\boldsymbol{j}_{BS}$$

MHD dynamo EMF, φ



- **φ, unknown variable**

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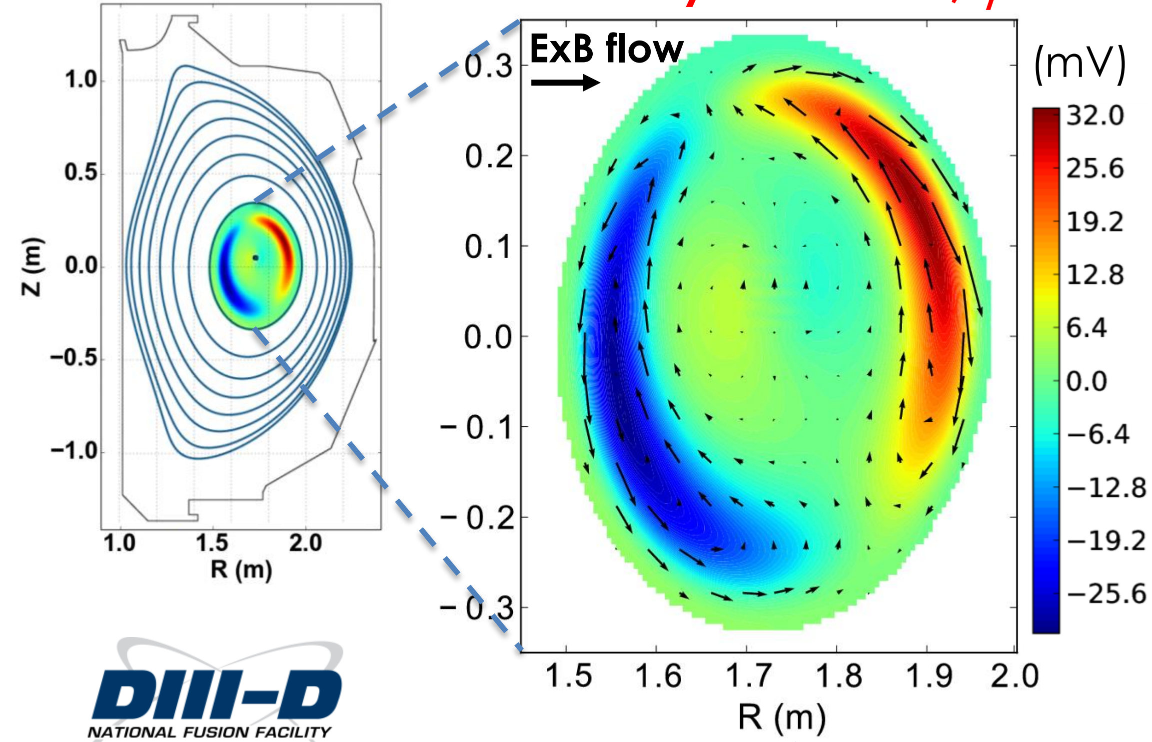

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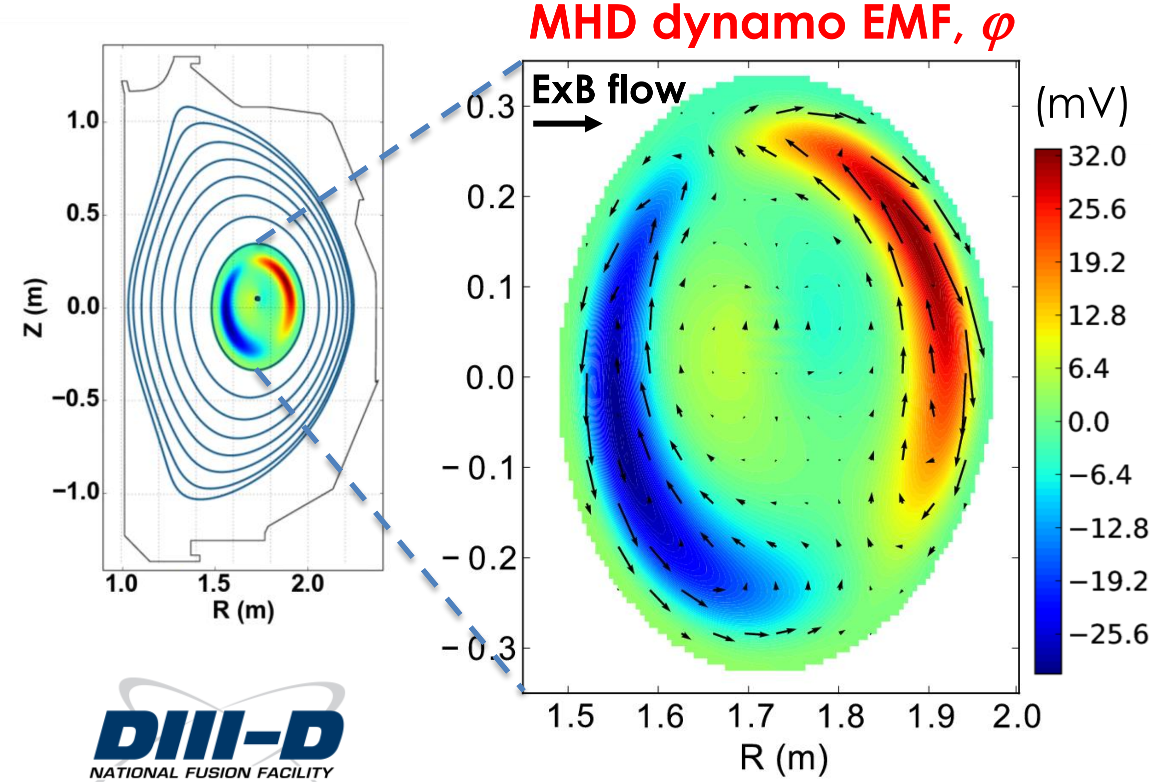

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- **2D quantities**: from ONETWO transport simulation mapped onto 3D equilibrium

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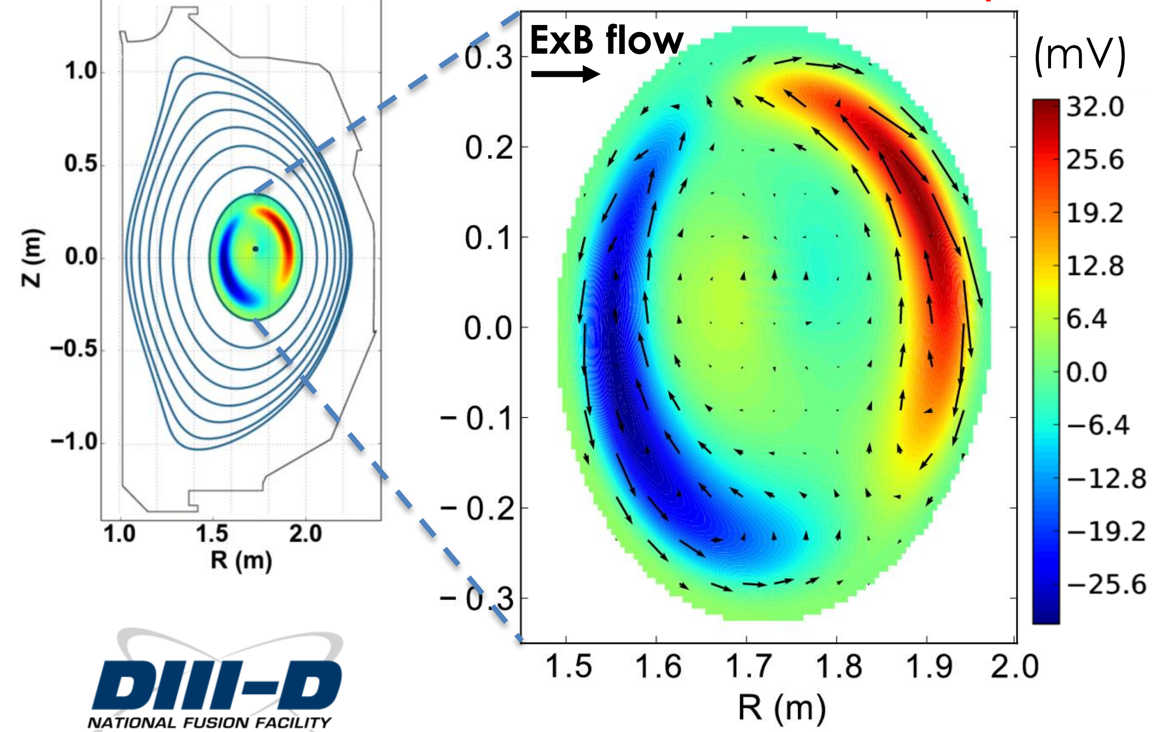
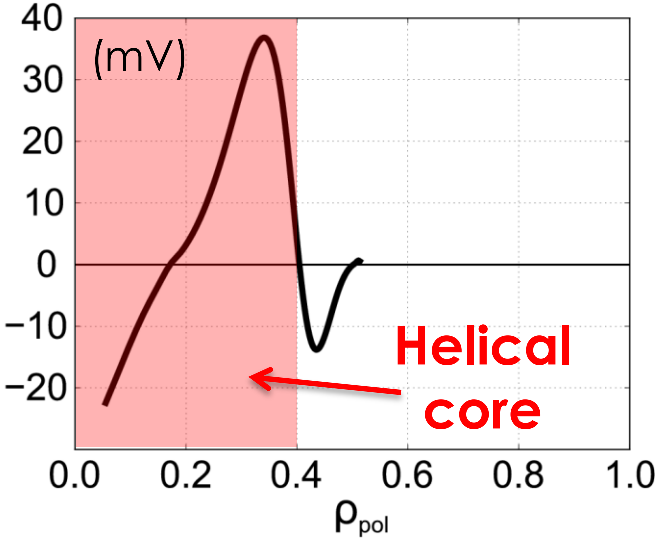


$$\boldsymbol{V}_{loop} = \langle -\nabla\boldsymbol{\varphi}\cdot\widehat{\boldsymbol{B}}\rangle 2\pi \boldsymbol{R}_0$$

consistent with measured polidal flux deficit ~10mV



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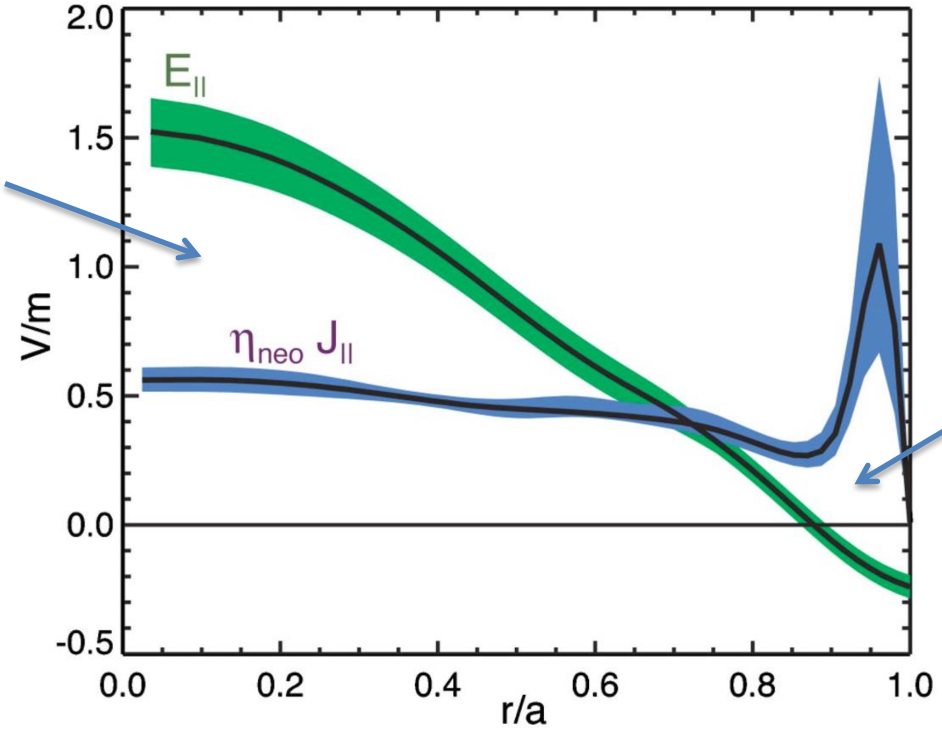
An MHD Dynamo EMF Maintains the Parallel Current Profile in the Reversed-Field Pinch

- **Confirmed by direct measurements of the MHD dynamo terms**

  S Ortolani, DD Schnack, Magnetohydrodyn. of Plasma Relaxation 1993,
  H Ji PRL 1994, PW Fontana PRL 2000, M Zuin PPCF 2009, DA Ennis PoP 2010, …



Dynamo limits the peaking of central Ohmic current

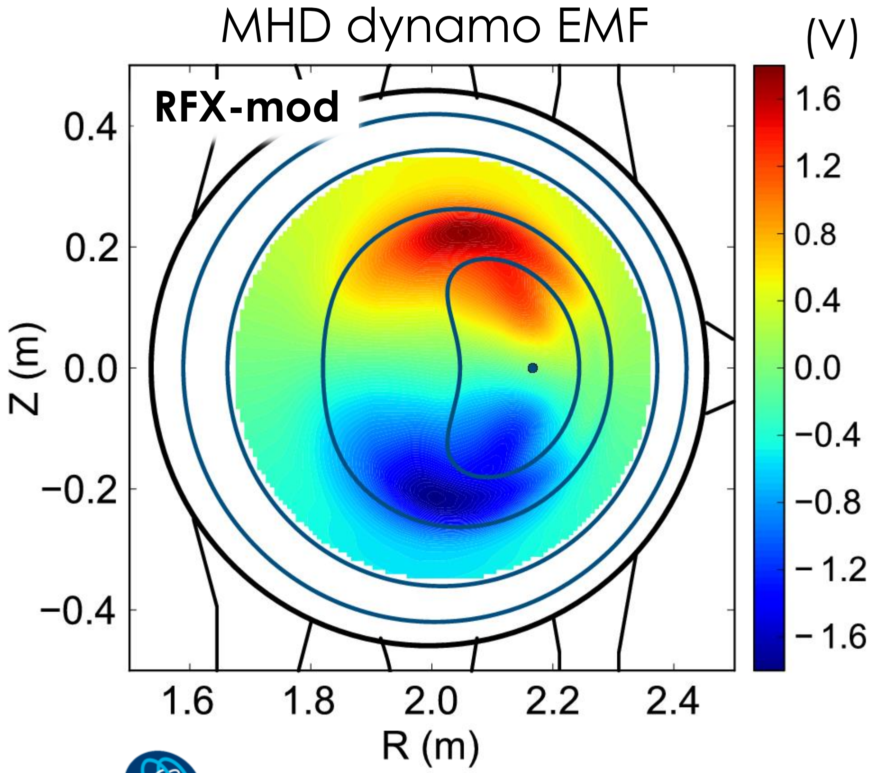
… and drives edge poloidal current

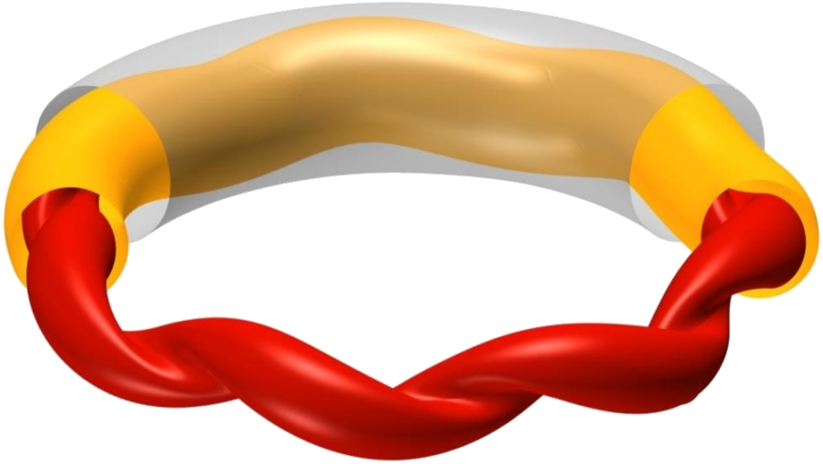
From JK Anderson PoP 2005

In Helical RFP Plasmas the MHD Dynamo is Mainly Provided by the Dominant Helicity

- **Helical RFP states form spontaneously at high-current >1MA**
- **Helical equilibrium from VMEC/V3FIT constrained by internal SXR measurements used to predict dynamo EMF in RFX-mod**

MHD dynamo EMF

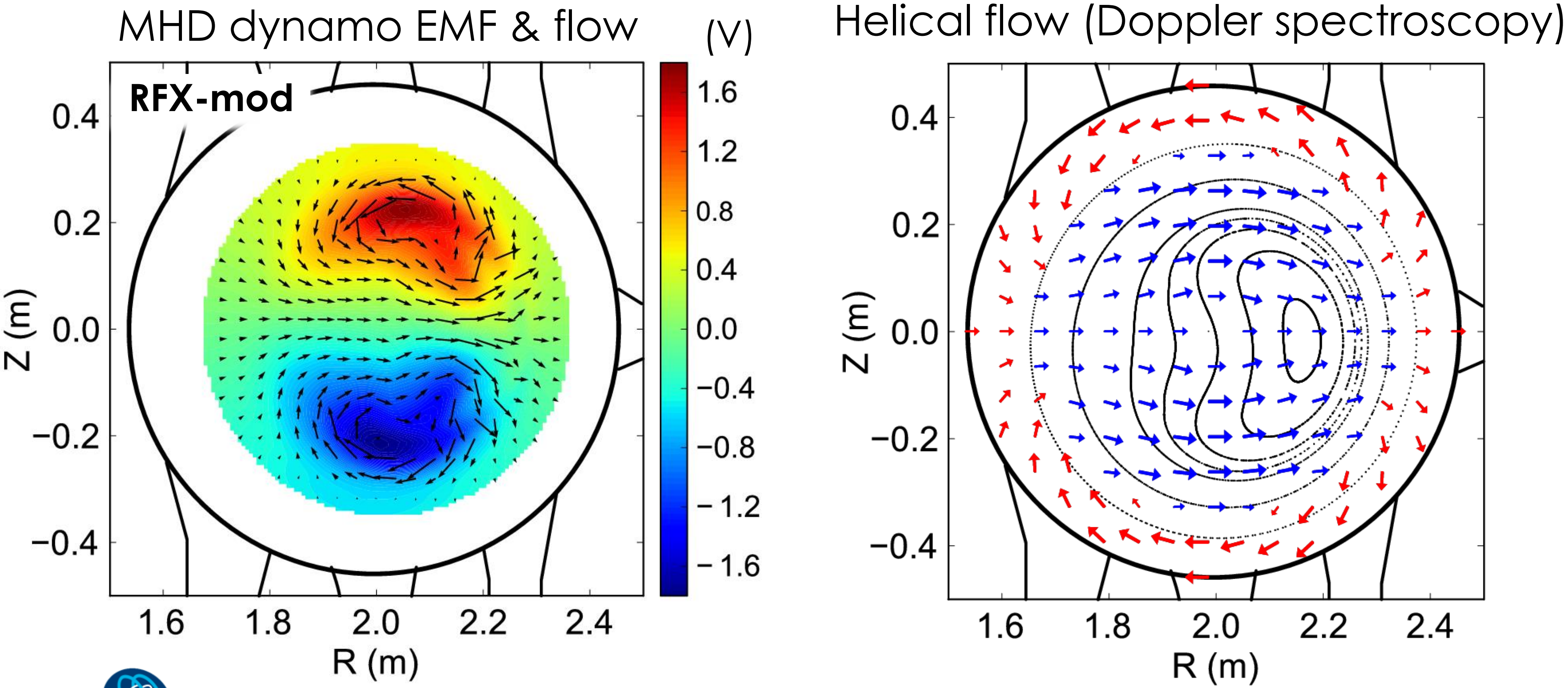




R Lorenzini Nature Phys 2009
D Terranova NF 2013
M Zuin OV/P-2, this conference

The Predicted MHD Dynamo Flow is Consistent with the Helical Flow Measured in Experiment

- **Both have a double convective cell structure**
  - Measured helical flow **≈ 1km/s** much larger than in tokamaks, because it must produce a much larger V_{loop} **≈ a few Volts**



P Piovesan PRL 2004 (MST)
F Bonomo NF 2011 (RFX-mod)

CONSORZIO RFX
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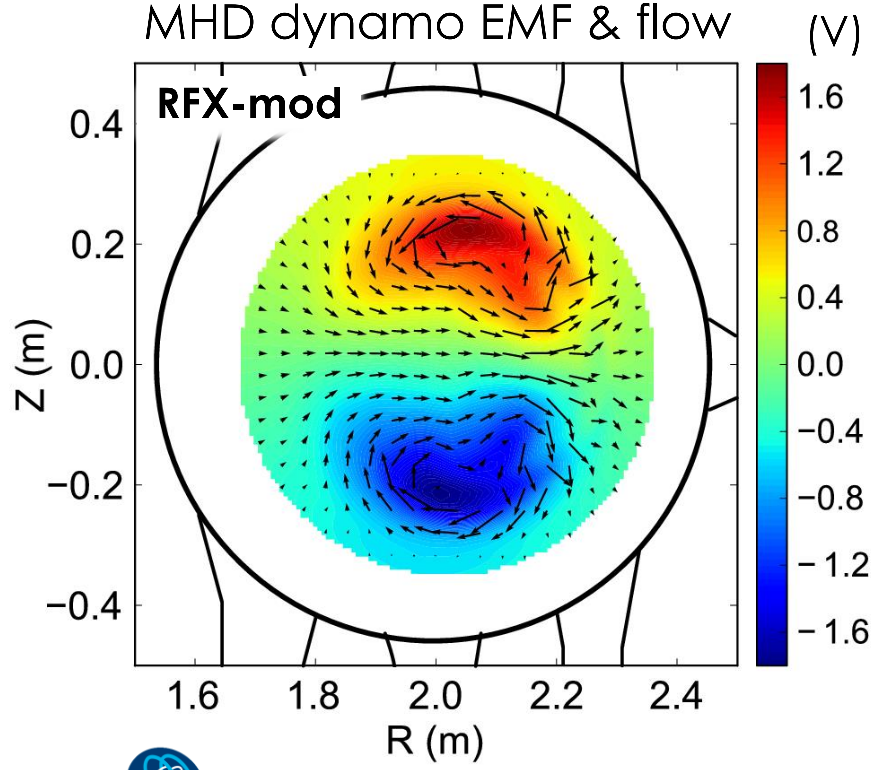
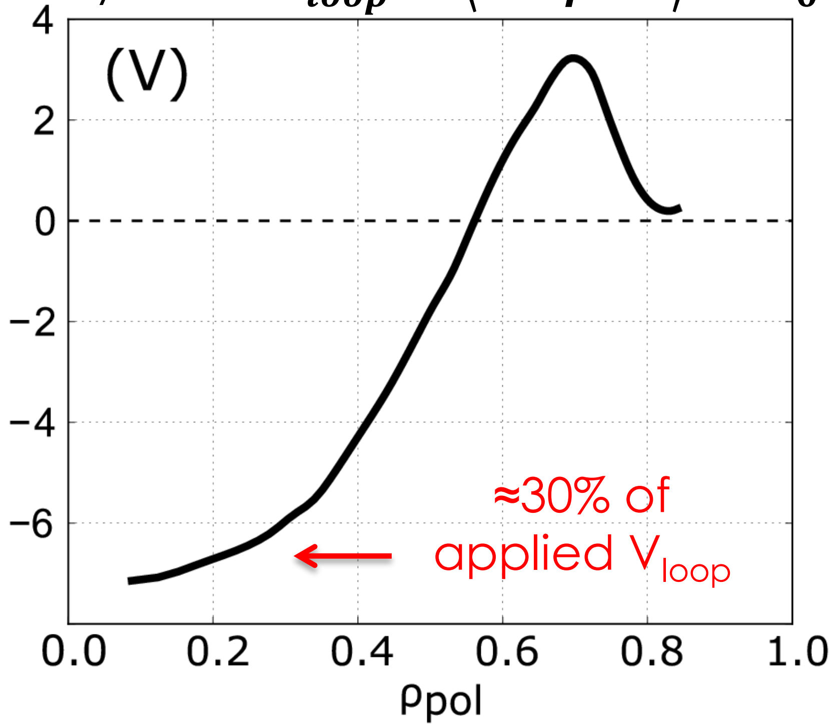
MHD dynamo EMF & flow



Dynamo $\boldsymbol{V_{loop}} = \langle -\nabla\boldsymbol{\varphi} \cdot \widehat{\boldsymbol{B}} \rangle 2\pi \boldsymbol{R_0}$



≈30% of applied V_{loop}

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Conclusions

- **The MHD dynamo model can explain current redistribution by MHD modes in RFP and tokamak plasmas**
  - The dynamo EMF can be **directly calculated from 3D equilibria** reconstructed from experimental data
- **The dynamo EMF can be produced in a continuous way with no need of transient events**
  - Expected to work in hybrid plasmas with suppressed ELMs

Conclusions … and Future Work

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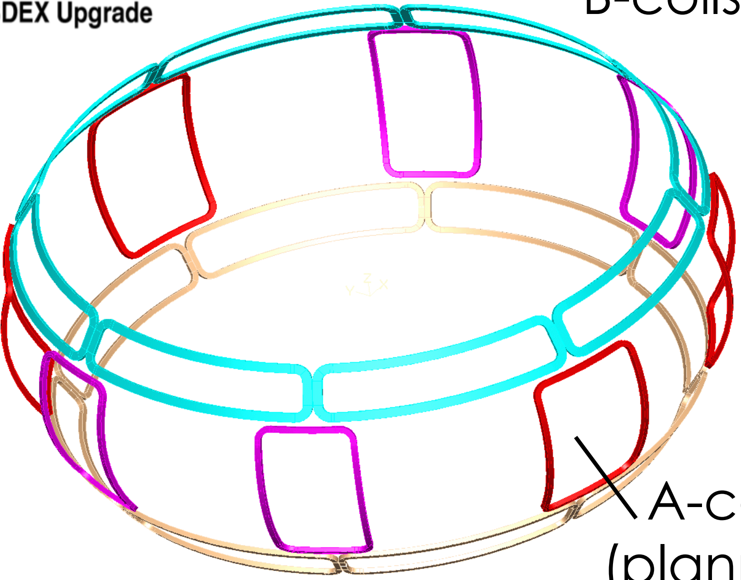
- **The dynamo EMF can be produced in a continuous way with no need of transient events**
  - Expected to work in hybrid plasmas with suppressed ELMs
- **Quantitative predictions for hybrid tokamak with a 3/2 tearing and scaling to future machines need more work**
  - Validated nonlinear MHD simulations of tearing modes
  - Add effects beyond 1-fluid MHD, e.g. fast ion transport by MHD
  - More experiments, 3D measurements, rigorous assessment of model/experiment uncertainties

Disclaimer

Back-up slides

Non-axisymmetric coils in ASDEX Upgrade and DIII-D

ASDEX Upgrade



8x2
B-coils

A-coils
(planned)

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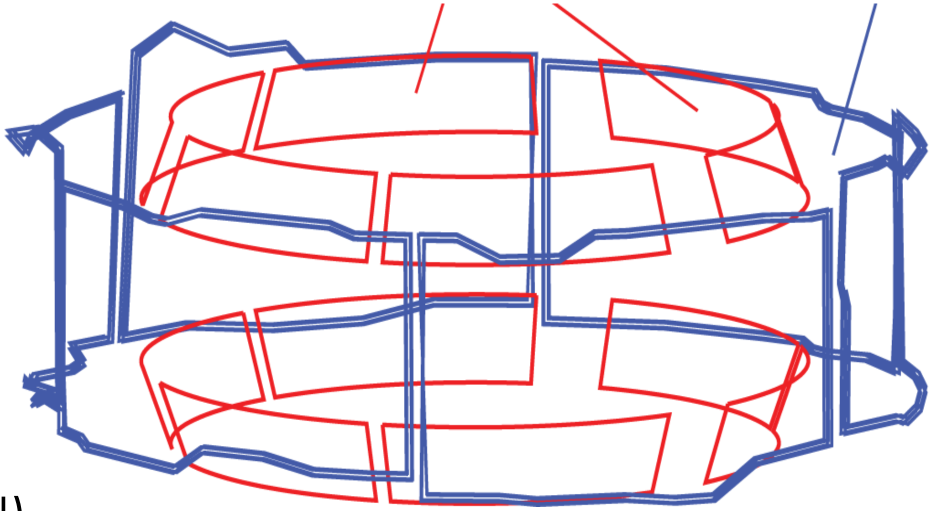


6x2
I-coils

C-coils

Flux states method to evaluate a poloidal flux deficit

- **$\psi_c I_p$ = W_{coil} = Energy provided by poloidal coils coupling with the plasma. Mutual inductance between coils and the plasma**
  - J_ϕ obtained from EFIT (magnetics + MSE), ψ_c from currents in the 18 poloidal field coils and E-coil

$$W_c = \frac{\mu_0}{4\pi}\iint \mathrm{d}V\,\mathrm{d}V'\,J_c J_\phi/\mathbf{r}$$

$$W_c = \int \mathrm{d}V\,J_\phi A_{\phi,c} = \int \mathrm{d}R\,\mathrm{d}z\,J_\phi \psi_c$$

$$\boxed{\Psi_c = \frac{1}{I_p}\int \mathrm{d}R\,\mathrm{d}z\,J_\phi \psi_c}$$

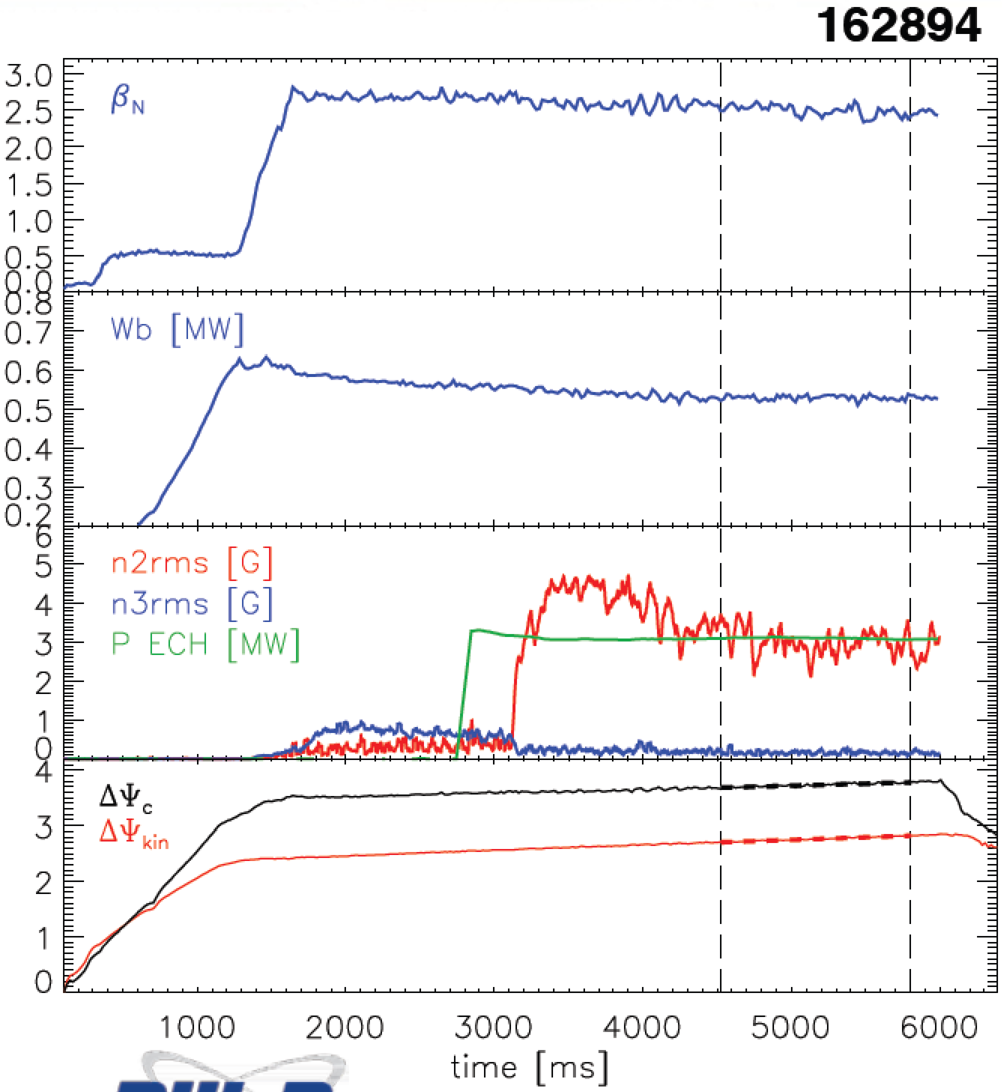
- **$\psi_{kin} I_p$ = Wkin = Work done by the electric field within the plasma. Amount of poloidal magnetic energy being converted to kinetic energy in the plasma**

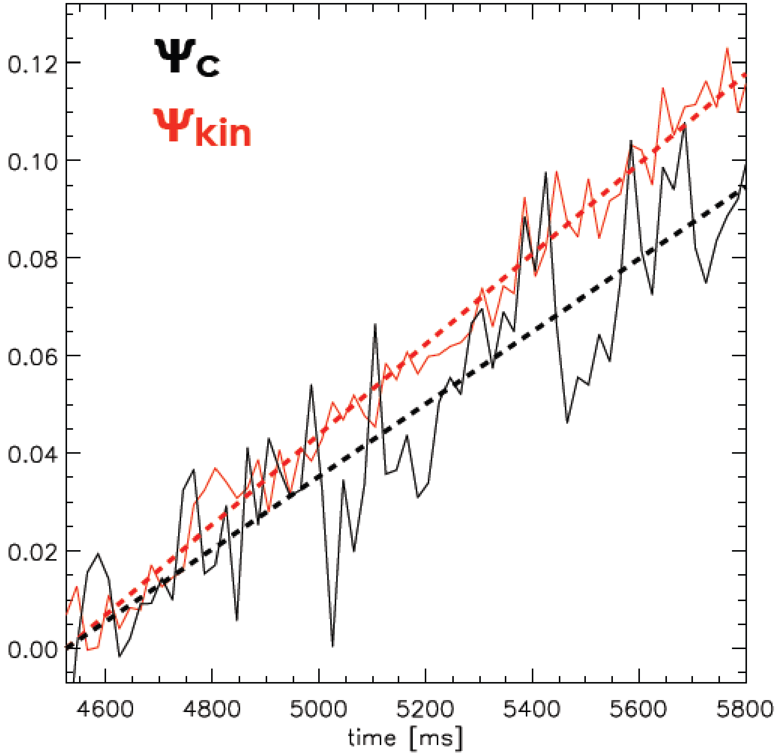
$$\frac{\mathrm{d}W_{kin}}{\mathrm{d}t} = -\int \mathrm{d}V\,J\cdot E$$

$$\boxed{\Psi_{kin} = \frac{1}{I_p}\int \mathrm{d}R\,\mathrm{d}z\,J_\phi \psi}$$

More details in T.C. Luce *et al*, *Inductive flux usage and its optimization in tokamak operation*, Nucl. Fusion **54** 093005 (2014)

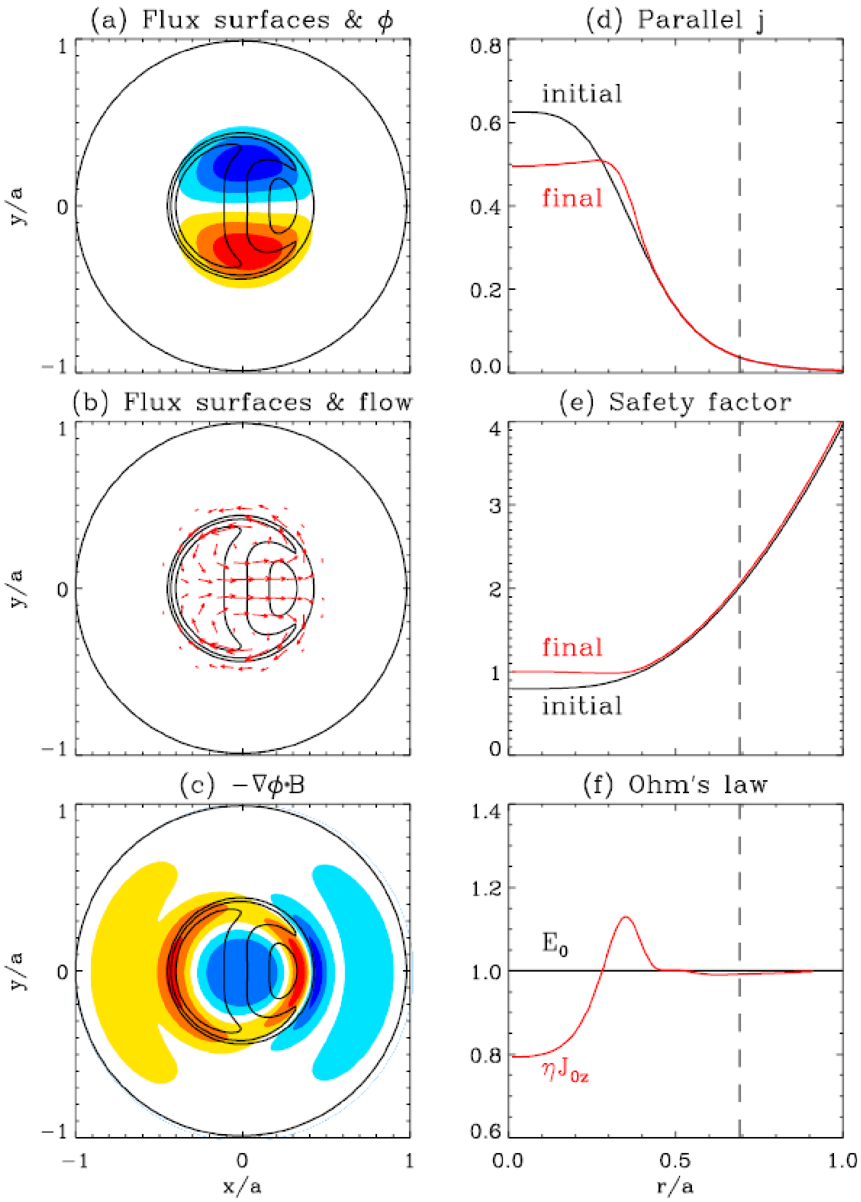
Poloidal flux deficit in a standard hybrid tokamak. Courtesy of NZ Taylor (GA)

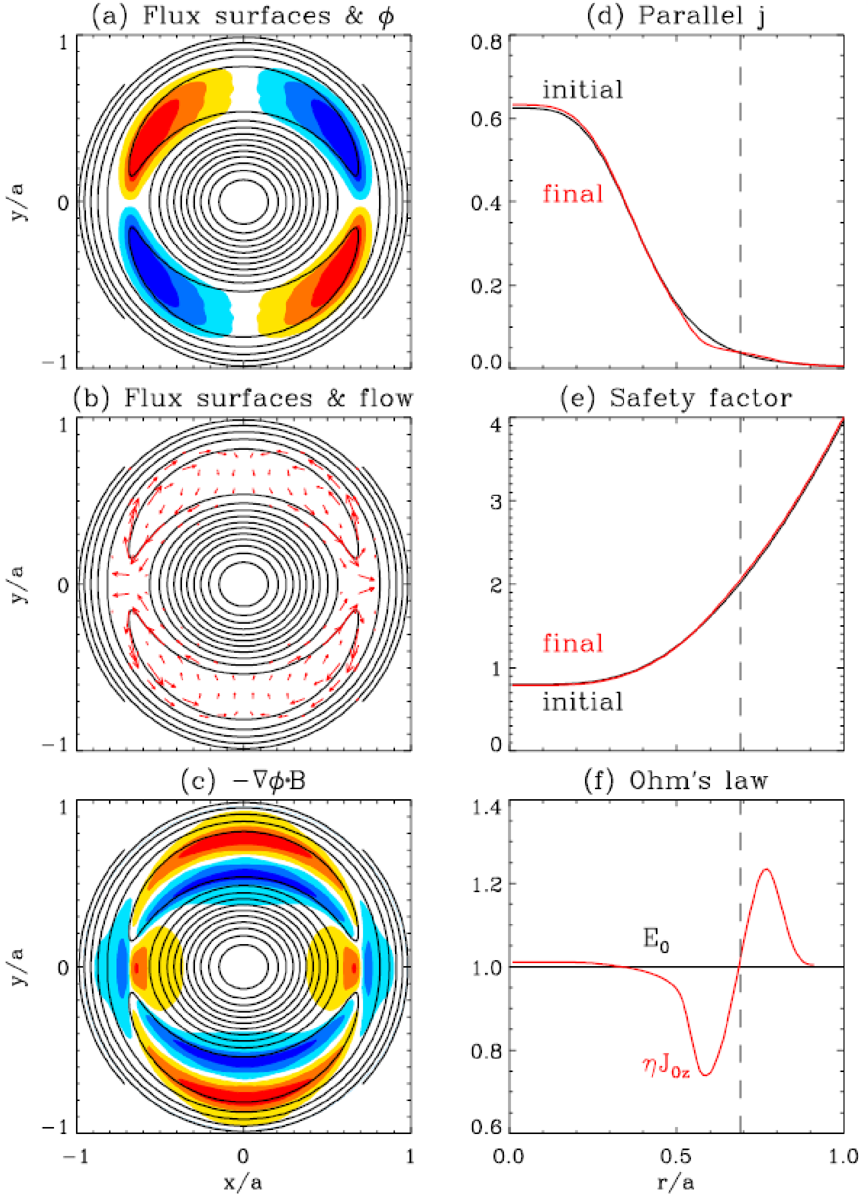




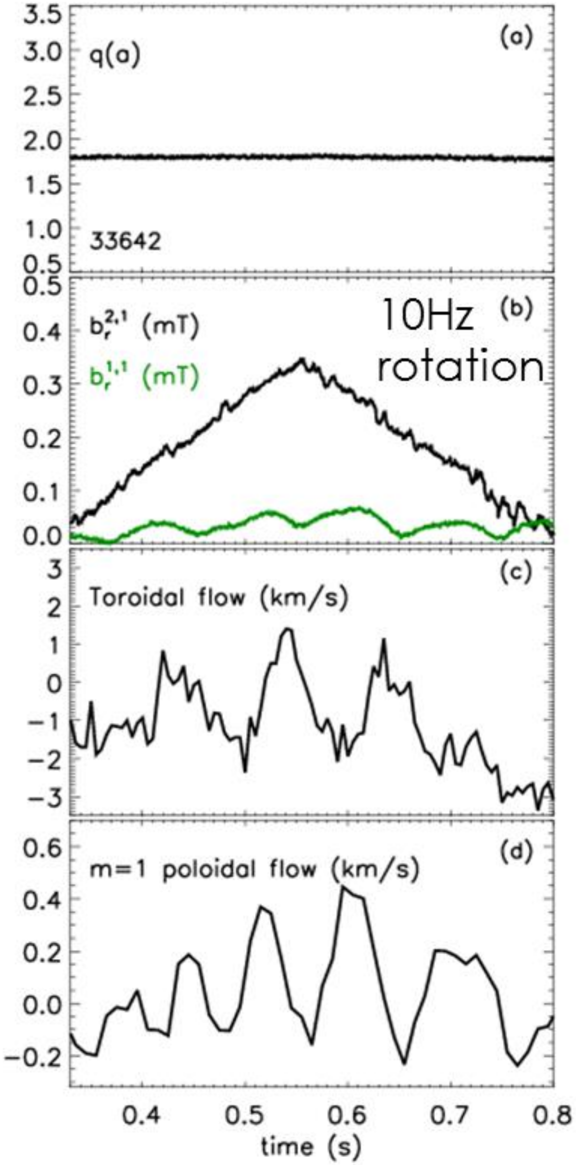
- Hybrid discharge where 3/2 NTM is destabilized
- Counter-ECCD applied to q=3/2 surface

MHD dynamo by 1/1 kink vs 2/1 tearing (SpeCyl code)

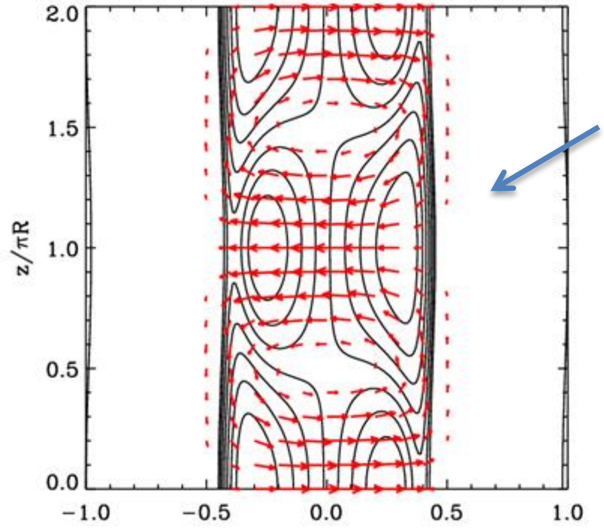




Helical flow of 1/1 kink in RFX-mod Ohmic tokamak

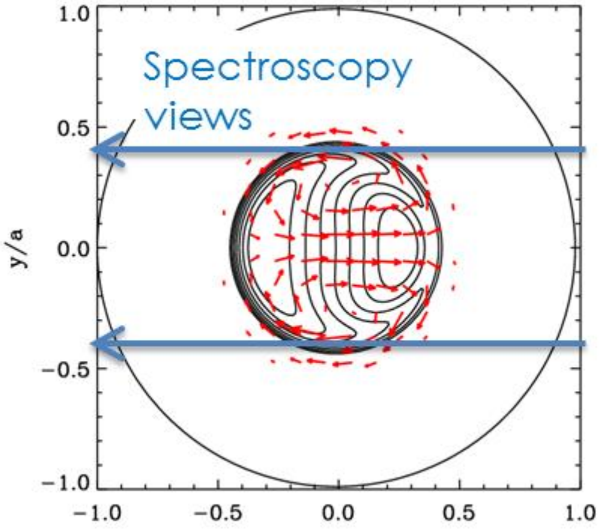


Toroidal cross-section



SpeCyl nonlinear MHD simulation

Poloidal cross-section



L. Piron et al, submitted to NF

In RFP nonlinear MHD simulations, dynamo is dominated by electrostatic fields even during fast relaxation events

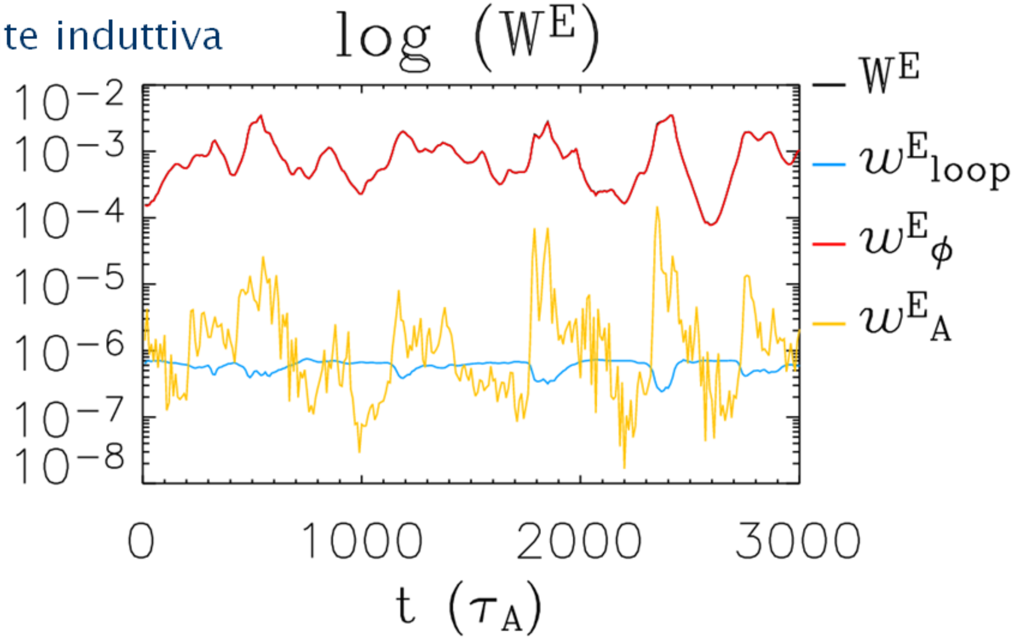
$$E = E_{loop} - \nabla\phi - \boxed{\frac{\partial A}{\partial t}} \longrightarrow \text{Componente induttiva}$$

$$\boxed{W^E = \tfrac{1}{2}\int_V E^2} = w^E_{loop} + w^E_\phi + w^E_A$$

$$\boxed{w^E_{loop} = \tfrac{1}{2}\int_V E\cdot E_{loop}}$$

$$\boxed{w^E_\phi = \tfrac{1}{2}\int_V E\cdot(-\nabla\phi)}$$

$$\boxed{w^E_A = \tfrac{1}{2}\int_V E\cdot\left(-\frac{\partial A}{\partial t}\right)}$$



From D Bonfiglio PRL 2005